N69-33983

CARBON FIBRE COMPOSITES IN ROCKET MOTOR SYSTEMS

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Bristol Aerojet Limited
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March 1969

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BY

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WESTON-SUPER-MARE
ENGLAND

MARCH 1969

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Edition or Date: Papers presented at 3d Brit. Interplanet. Soc. Symp. on Mater. in Space Technol., Bristol, Engl.

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/ / Periodical

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N69-33983# Bristol Aerojet, Ltd., Banwell (England).

CARBON FIBRE COMPOSITES IN ROCKET MOTOR SYSTEMS

T. A. Trigg Mar. 1969 21 p refs Presented at the 3d Brit. Interplanet. Soc. Symp. on Mater. in Space Technol., Bristol, Engl., 9–11 Apr. 1969

Avail: CFSTI

Although carbon is contained in around 90% of all known chemical compounds, it has only recently had any marked effect as a structural material. This has been made possible by the discovery that certain synthetic polymeric fibres can be reduced to pure carbon or graphite with attractive mechanical properties and that these can subsequently be used for reinforcing composite materials. In rocket motor structures many of the applications call for materials that will withstand high temperatures and in this direction increasing use is being made of carbon/resin materials as ablative liners. These have been shown to have improved properties over more conventional asbestos/resin materials, with an added bonus of weight advantage. The recent introduction of high modulus carbon fibres into the resin composite technology has given impetus to the development, particularly in the area of rocket motor case manufacture. Although mechanical performance data is still limited, there is sufficient evidence to indicate that the basic weight of an unfilled motor and expansion cone may be halved by use of carbon fibre composites to the exclusion of all conventional materials.

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CARBON FIBRE REINFORCED PLASTIC COMPONENTS FOR AEROSPACE USE

M. W. Jones 1969 19 p refs Presented at the 3d Brit. Interplanet. Soc. Symp. on Mater. in Space Technol., Bristol, Engl., 9–11 Apr. 1969

Avail: CFSTI

An outline is given of the development history of RAE carbon fibre reinforced plastics. Initially, development was inhibited by poor interlaminar shear strength. However, composite properties have improved since the advent of various surface treatments derived by the fibre producers. Present work indicates certain criteria by which resins are selected for use as a matrix with the two available types of RAE fibre. These are more critical for filament wound cylindrical components than for pressed flat laminates, as shown by levels of fibre compaction achieved on hoop wound NOL rings and helically wound tubes. At present, the strength data fall well below that available if the full strength of the single fibre or bundle is utilised. However, the majority of the fibre stiffness has been achieved in unidirectional composites. Illustrations are shown of a carbon fibre reinforced plastic and honeycomb sandwich satellite structure which has been constructed to investigate the efficacy of methods selected for laminating polygonal cylindrical shapes, the subsequent adhesive bonding and the final machining to complete the structural assembly.

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S U M M A R Y

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The recent introduction of high modulus carbon fibres into the resin composite technology has given impetus to the development, particularly in the area of rocket motor case manufacture. Although mechanical performance data is still limited, there is sufficient evidence to indicate that the basic weight of an unfilled motor and expansion cone may be halved by use of carbon fibre composites to the exclusion of all conventional materials.

1. INTRODUCTION

In order to appreciate the philosophy behind the present use or proposed use of carbon fibre composites it will be helpful to give some consideration to the nature of the raw material. Probably 90% of all known chemical compounds contain the element carbon but at the same time its use as a material in its own right has had little effect on the Engineering Industry and practically none for structural purposes until very recently.

The basic properties of carbon have several attractive features particularly relevant to rocket conditions, not least of which is the high sublimation point of 3,649°C. In addition, its strength characteristics tend to increase with increasing temperature and at lower temperatures it is a remarkably inert material.

Unfortunately, there are disadvantages not least of which is the form in which it is readily obtainable. The material in its natural state is either rare in the form of diamond or graphite or too impure to consider as an engineering material, and many of the forms of manufactured carbon, such as charcoal or coke, have structures which render them virtually useless. One method by which a more consistent engineering material may be made is to crush a carbon product (such as coke) into a powder, mix it with a pitch, mould it roughly to the shape required and heat it to around 850°C. in an inert atmosphere. This produces a porous version of the desired material and further vacuum impregnation with more pitch and repeated firings will produce high grade materials; final baking in excess of 2,000°C. produces graphite and by carefully controlling the conditions, materials with some crystallized orientation can be obtained.

An even purer form of carbon, known as pyrolytic graphite, can be produced by actually depositing carbon atoms from an electrode in a vacuum furnace at the graphitizing temperature. This material is highly orientated and typical properties, compared with those for a graphite crystal and two high modulus fibres, are shown in Table I.

TABLE I

MECHANICAL PROPERTIES OF GRAPHITE

	Pyrolytic Graphite	Graphite Whisker	Type I Fibre	Type II Fibre
Relative Density	1.9 - 2.2	2.25	2.0	1.77
Tensile Strength (MN/m^2) "a" -	70	20,000	1,400	2,000
Tensile Strength (MN/m^2) "b" -	3.5			
Tensile Modulus (GN/m^2) "a" -	28	700	400	240
Interlaminer Shear Strength (MN/m^2)	3.5	-	-	-

Note: The above figures are typical only.

For pyrolytic graphite, "a" direction is along the crystal growth and "b" direction is across the planes.

1. INTRODUCTION (Continued)

From these figures it will be seen that whilst mechanical properties for pyrolytic graphite in one direction are attractive, the material is so anisotropic that strength across the plane of orientation, together with associated interlaminar shear strength, is such as to preclude its use for structural purposes, hence the desire for fibre composites.

The conception of using graphite in the fibrous form is not entirely new and, in fact, Edison's first electric light bulb filaments were made using carbonized bamboo fibres. However, it is unlikely that these would have had any reasonable strength.

In the 1950's it was discovered that flexible carbon fibres could be produced by the baking, under suitable conditions, of cellulosic fibres. The empirical equation for this process is fairly simple and can be written:-

$$(C_6 H_{10} O_5)_n \longrightarrow 6_n C + 5_n H_2O$$

However, the process has been described as a little more complicated[1]. As the temperature is raised the ring hydroxyl and hydrogen molecules come off as water; by about 700°C. most of the dehydration, demethanization and aromatization is complete. Further heating produces minor out-gassing of carbon monoxide, carbon dioxide, hydrogen and a few complex tars, and raising the temperature to the order of 2,800°C. produces graphitic fibres. Typical assay figures for carbon content are 94% for the carbonized and 99% for the graphitized fibres, with ash contents of up to 1.2% and less than 0.1%, respectively.

The main advantage of this process is that it can be extended to treat any type of stock, i.e. cloth, tape, yarn, etc., made from the cellulosic fibre, thus, for the first time, carbon and graphite reinforcing materials similar to the glass materials already on the market became available and the true era of carbon composites could begin.

The next milestone in the history of carbon composites came in the mid 1960's when new techniques were discovered for the treatment of cellulosic and acrylonitrile fibres to produce carbon or graphite filament having properties approaching those of the basic crystal.

These high modulus fibres, as they became known, are still in their infancy and supplies are restricted and expensive. Nevertheless, they have opened up a completely new field of reinforced composites and a separate section is devoted to them later in this paper.

Today there are numerous methods of producing high quality carbon and graphite, both in massive and in fibrous form; many of these processes are patented and some carefully guarded under cloaks of security. Because of the nature of the raw materials and treatments, a product can start out as a true composite of carbon and some other material and finish up virtually as a 100% carbon structure. Progress has thus taken us from solid carbon, through carbon fibre composites, and back to a solid carbon but with a potentially far higher standard of mechanical properties.

2. ABLATIVE MATERIALS

During the process of ablation, a series of distinct functions occur in rapid succession. The hot gas flowing over the surface transfers some of its heat to the ablation material, which increases in temperature, the increase being a function of several parameters one of which is the rate of heat sink into the cooler part of the structure. As the temperature reaches a certain level the surface material chars and absorbs some of the heat input, at the same time organic materials will decompose and give off gasses, which are swept along the surface to form a thin insulating barrier. The char layer is removed by erosion and decomposition, the erosion being a function of the rate of mass flow over the surface and decomposition a function of heat and oxidation. Thus, as the char is removed so will the heat sink deeper resulting in more char until the process has completely removed the ablation material.

2.1 Fibre and Cloth Moulding Compounds

For large scale production of complicated shapes, using any plastics material, one of the simplest manufacturing methods is that of moulding, either by injection, compression, displacement or transfer. It was therefore logical that as soon as fibrous carbon and graphite came on to the market efforts should be devoted to the development and manufacture of moulding compounds based on these materials. In this country materials were developed using carbon wool, graphite powder and a phenolic resin. Mixtures were produced to give improved ablation resistance over more conventional moulding compounds. They were based on materials then available and are still being manufactured for development purposes today.

Different phenolic resins have been used in these mixtures and at the present time there is still insufficient evidence to show a decided preference for either a resol or a novolak. Generally speaking, the novolak based compound gives improved moulding characteristics but there is some evidence to suggest that the resol might be superior for ablation resistance.

The addition of graphite powder of 300 mesh size was primarily intended to improve the general appearance of mouldings and to increase somewhat the total carbon content. It was also hoped that the additional fine graphite powder, infiltrating the spaces between the wool, would improve general ablation resistance.

In addition to the compounding of simple moulding materials from carbon fibres and resin, a further method has been used extensively in the United States and, in effect, consists of taking impregnated carbon or graphite cloth and dicing it into $\frac{1}{2}$ in. x $\frac{1}{2}$ in. squares. One advantage of this method of manufacture is that it lends itself to the utilization of pre-impregnated stock that has probably been rejected for another reason. If, for example, a fabricator calls for a pre-preg. cloth with a given degree of tack and, due to a fault in the pre-impregnating process the material is overdried or 'boardy', this may be perfectly acceptable (and could even need further pre-drying) for a high pressure moulding. The properties are good and ablation resistance is similar to that of a cloth laminate but, needless to say, if one is not using otherwise rejected material, it will

2.1 Fibre and Cloth Moulding Compounds (Continued)

be expensive compared with a bulk fibre type of compound.

Typical mechanical properties of these moulding compounds are given in Table II. Comparisons of ablative performance are given later in the paper.

TABLE II

MECHANICAL PROPERTIES OF CARBON/PHENOLIC MOULDING MATERIALS

Reinforcement	Flexural Strength MN/m^2	Flexural Modulus GN/m^2	Relative Density
Carbon Wool	90	15	1.44
Carbon Wool/Graphite	93	12	1.5
High Modulus $\frac{1}{2}$ in. - 1 in.	104	18	1.48
Chopped Squares $\frac{1}{2}$ in. x $\frac{1}{2}$ in.	100	15	1.47
Asbestos - for comparison	100	12	1.78

Note: All moulding materials, with exception of chopped squares, were manufactured at Bristol Aerojet Limited.

Chopped Squares - U.S. Polymeric FM.5014 WG - Data Sheet Figures.

2.2 Edgewise Tape Winding and Rosette Lay-up

Much of the development concerned with ablation has been associated with the development of materials that give a tenacious char, resins which decompose to give effective cooling layers - again with a good char, and methods of construction to provide adequate heat sink from the hot surface. In the case of fibrous materials, the thermal conductivity or heat sink along the fibres or along a piece of cloth is far higher than across the laminae. This was appreciated about ten years ago when attempts were made to fabricate a parallel blast pipe liner with a fringed material, the fibres being radial to the axis of flow. Unfortunately, at that time the practical difficulties of laying a fringe material in this manner were greater than was envisaged. In more recent years H.I.T.C.O. * have marketed a bias cut tape that has led to the manufacture of such structures by the process of edgewise winding.

* H.I. Thompson Co., Gardena, California.

2.2 Edgewise Tape Winding and Rosette Lay-up (Continued)

By taking woven broadstock after impregnation with the required resin, cutting at 45°, joining the pieces together and slitting it along its length, one has material whose warp and weft strands are at 45° to the edges and which will deform by movement of these strands over one another. It is possible, therefore, to produce a liner with the tape wound at an angle to the axis. Figure 1 illustrates this.

A number of items have been produced in edgewise wound graphite tape and Figure 2 shows a typical example of a graphite tape wound cone with an asbestos/phenolic overlay.

An almost direct comparison has been made by H.I.T.C.O.[1] on an edgewise wound throat section using carbon and graphite cloth under the same conditions. A set of results for these throats is given in Table III. The items were, in fact, constructed of bias tape, wound at 35° to the axis and cured at a pressure of 68 bar. From these figures it can be seen that carbon, in fact, behaves slightly better than graphite, although the H.I.T.C.O. paper referred to limited data and added that specific conclusions were difficult to formulate. It was thought that the superior performance of the carbon could be attributed to its low thermal conductivity and higher strength; nevertheless the different resin content could also have some effect on the properties.

TABLE III

COMPARISON BETWEEN CARBON AND GRAPHITE COMPOSITES

Motor - Solid Propellant - Mass Flow 24.75 Kg.
- Burning Time 70 sec. approx.
- Average Chamber Pressure 25 bar.

Carbon Material - 8 shaft satin weave 42% resin

Graphite Material - Plain weave 34% resin

	Carbon	Graphite
Initial Diameter (mm.)	111.45	111.56
After Firing Diameter (mm.)	130.61	134.57
Area Increase (%)	37.32	45.51
Radial Throat Erosion rate (mm/sec.)	0.131	0.159

The above figures have been metricated from H.I.T.C.O. publication by R.B. Millington, 1965.[1]

2.2 Edgewise Tape Winding and Rosette Lay-up (Continued)

The term 'Rosette'* lay-up refers to a principle of producing a component by the pressure curing of a series of petals or leaves of material formed into a rosette. This has the effect of distributing any discontinuities around the whole circumference of the component. A better idea of the construction of such a component may be seen from Fig. 3 showing the distribution of petals around a rocket motor end plate liner.

As will be appreciated, this type of construction is ideally suited to components for which a petal shape can easily be developed. These can be laid up on a male or female former and cured by the application of pressure. For most of the components associated with rocket motors a normal square weave type of material is quite suitable - it gives fairly isometric properties and holds its shape well when cut. For less gentle contours satin weave material is to be preferred as this, because of its fewer interlocks, allows a greater degree of drape. Both these materials are available in either carbon or graphite.

One major advantage of this type of construction is the almost unlimited size of components which can be made. It has been shown that in order to produce an acceptable laminate, an effective cure can be achieved by the application of vacuum pressure only. Ideally, however, to achieve the optimum results, laminates should be cured under a high pressure (1,000 lbf/sq.in. - 68 bar). This is normally carried out in a hydroclave which, because of these high pressures and the temperature of operation (up to 200°C), is an expensive piece of equipment. At the present time the largest vessel known to be operating at these conditions in this country is 18 in. dia. x 18 in. deep, and over the last year or so this has been used extensively for the manufacture of end plate and blast pipe liners, expansion cones, and other rocket motor items in various materials, and using several methods of construction.

To date, the experience of firing 'Rosette' lay-up items manufactured in carbon or graphite has been rather limited in this country and while end plate liners have fired satisfactorily, parallel blast pipe liners have tended to delaminate. This is to a certain extent understandable, since the pressure on the end plate liner tends to keep the petals closed, whilst in the blast pipe the hot gasses passing along the petal edges cause the delamination. Exercises are now being carried out to study the effect of spiralling the laminates in the blast pipe liner in order to avoid this delamination. Figs. 4 and 5 illustrate the fabrication of such a liner and the spiralling that results.

* Rosette - Registered Trade Mark of H.I.T.C.O.

2.2 Edgewise Tape Winding and Rosette Lay-up (Continued)

As with other items manufactured for rocket motor purposes, it is difficult to compare materials or methods of construction unless they are fired under identical or near identical conditions. The Ministry of Technology, however, at the Rocket Propulsion Establishment, have an 8 in. diameter test motor that can be fired reasonably economically with one of several standard propellants. Into this motor can be fitted similar components manufactured in different materials by different methods. Over the years a considerable number of firings have been made and Table IV indicates the order of erosion rate which might be expected for various constructions. It will be seen that the carbon or graphite materials are superior to the more general asbestos/phenolic materials and also lighter in weight.

Unfortunately, erosion figures on their own do not tell the whole story and very often some other property could be that which leads one to a final choice. For example, in comparing an edgewise tape wound component with a 'rosette' laid up item of similar size and shape, the heat transfer through the two will be quite different and the ratio of specific conductivity could be quite conceivably in the order of 3 to 1 - the edgewise wound component having the higher value. Needless to say, this particular consideration becomes a major parameter if the function of the ablation liner is also to be coupled with that of a thermal insulant, as in a structure where there is a metal backing.

TABLE IV

COMPARATIVE EROSION RATE OF ROCKET MOTOR COMPONENTS

Material	PROPELLANT NO. 1		PROPELLANT NO. 2	
	End Plate	Blast Pipe	End Plate	Blast Pipe
Carbon/Phenolic Mouldings	0.05	0.075	0.06	0.025
Graphite/Phenolic Tape Wound	-	0.1	-	0.1
Graphite/Phenolic Rosette Lay-up	0.025	Delaminated	Not Tested	Not Tested
Asbestos/Phenolic For Comparison	0.125	0.125	0.15	0.175

All erosion rates are typical only and tabulated in mm/sec.

Firing Conditions

Burning Pressure	41 bar.
Mass discharge	0.0027 Kg/sq.mm./sec.
Flame Temperature	Propellant No.1 - 2777°K
	Propellant No.2 - 3340°K

3. HIGH MODULUS FIBRES AND THEIR COMPOSITES

As recently as the mid 1960's, the latest major development in carbon fibre composites was made possible by the availability of a high modulus fibre in limited quantity. Research in Britain had been carried out since 1962 by Rolls-Royce Limited and the R.A.E., Farnborough, and the technological break-through was proclaimed by R.A.E.(2) in an article describing high modulus, high strength, carbon fibres that had been developed and were in initial production. The properties of these fibres were given, showing tensile strengths of up to 300×10^3 lbf/sq.in. ($2,000$ MN/m^2) and a tensile modulus of 60×10^6 lbf/sq.in. (400 GN/m^2). The first fibres produced were in metre lengths and the immediate potentiality of this type of reinforcement was realised, not only for rocket systems but also for aerospace and other applications. Within a year or so long lengths of material became available and fibre up to 1,000 ft. in length is now commercially available, although delivery is still restricted and the price high.

This high modulus fibre is being generally marketed in two distinct types, known as Type I and Type II. The Type I fibre has a modulus of around 60×10^6 lbf/sq.in. (400 GN/m^2) with a tensile strength of around 200×10^3 lbf/sq.in. (1,400 MN/m^2). The Type II fibre has around 35×10^6 lbf/sq.in. (240 GN/m^2) modulus and 300×10^3 lbf/sq.in. (2,000 MN/m^2) strength. Although most of the commercial production of all fibres is in batch quantities, this is not necessarily so for Type II, and at the R.A.E. their process for this fibre is truly continuous and designed to run non-stop for months on end, with an obvious economic advantage. At the present state of knowledge, however, it is possible that Type I fibre may continue to be made by the batch process, in which case there would appear to be less likelihood of the price of this material falling to the same level as Type II.

In Britain the majority of high modulus fibres are supplied in lengths or tows of discrete filaments. The number of filaments in a tow is obviously determined by the economics and the present standard appears to be 10,000 although the R.A.E. at Farnborough are working with tows of filaments down to 2,500. The filaments themselves are exceedingly fine (7 - 8 micron or 0.00028 - 0.00032 in.) and extreme care is necessary in order to avoid as far as possible damage to these filaments during the processing.

The American high modulus fibre, unlike the British, is generally supplied in the form of a twisted yarn but to date there is insufficient evidence to suggest that this is any better than the straight tow. Yet another form of high modulus graphite that has been evaluated, is a continuous staple yarn produced from short length fibres. It is unlikely, however, that this will continue to hold much attraction, particularly for the Type II fibre; its possible use for Type I will depend once again on the economics of manufacture.

3.1 Motor Cases and Pressure Vessels

In order to appreciate one particular and major interest in these high modulus fibres it is necessary to consider a little of the history of the fibre composite rocket motor case.

3.1 Motor Cases and Pressure Vessels (Continued)

It is now over ten years since the first glass fibre/resin motor case was made and fired successfully in this country. This particular motor was a straight tube, 9 in. diameter and approximately 10 ft. long. It was helically wound over a latex liner on a straight parallel mandrel. The ends were of aluminium, open ended, bonded to the tube and over-wound with glass tape. A solid cordite charge was used and the ultimate hoop composite wall stresses being realised at that time, using commercial glass rovings, were in the region of 75,000 lbf/sq.in. (517 MN/m^2).

With the introduction of plastic propellant bonded to the wall of the case designs became more complicated, and with higher strength glasses ultimate composite wall stresses in the order of 170,000 lbf/sq.in. (1,172 MN/m^2) are being achieved. Unfortunately, however, the modulus of glass is so low that the strain at these high wall stresses can be too much for the propellant. If the design of the motor cases is strain limited, the weight advantage over high strength steels is lost and the glass/resin motor case may never really become a practical consideration in this country.

With the advent of high modulus carbon fibres, however, the concept of a fibre/resin motor case again appears attractive provided all the problems of using these materials can be overcome and, if possible, the basic raw material price can be reduced.

It is a difficult task to compare the properties and performance of structures manufactured from two such dissimilar types of material as metal and fibre composite. Most readers will have seen the usual properties charts quoting fibre properties and compared them with those of a high tensile steel, noting that the former material has only a quarter of the weight of the latter. This, in fact, means very little, and an attempt has been made to give a clearer comparison in Table V, which quotes figures for actual components rather than the raw materials.

At the time of writing this paper, a carbon fibre rocket case in continuous high modulus carbon has not, to the writer's knowledge, been made and fired in this country. This is mainly on the grounds of most effective use of the limited supplies of material available. However, a winding trial has been made using sub-standard material in which a 6 in. diameter solid propellant rocket motor case was manufactured. A carbon cloth 'rosette' laid up expansion cone was added and this assembly is shown in Fig. 6. It is hoped that within a short time the exercise will have been repeated, using correct material, and a firing made.

Small scale pressure vessels have been filament wound in Type II material using epoxy resin; strain readings during test have confirmed the quoted modulus. Ultimate strength figures, however, have not been so encouraging although one recent test on a 4 in. diameter vessel, using surface treated Type II Morganite fibre, has given over 80% of the strength realised on a N.O.L. ring test and approaching 70% of the ultimate design strength. The failure to achieve the full ultimate

3.1 Motor Cases and Pressure Vessels (Continued)

strength in structures has caused considerable consternation and has been generally attributed to the low interlaminar shear strength and to specific design problems associated with high modulus fibre composites. Methods of overcoming the problem have been studied - some complicated and expensive such as the growing of silicon carbide whiskers on to the fibres[3], some involving simpler surface treatment of the fibres, and others concentrated on the choice and application of the resin systems. At Bristol Aerojet it is considered necessary, or at least most desirable, that all continuous fibre for filament winding should be pre-impregnated, and a plant is already working, enabling different resin systems to be used at controlled viscosities and "B" staging conditions. A second and larger facility is in course of construction.

TABLE V

COMPARISON BETWEEN STEEL, GLASS/RESIN AND CARBON/RESIN VESSELS

	120T Maraging Steel	Glass S.994	Graphite		
			Actual (3) Type II	Potential Type II	Potential Type I
Ultimate Stress in fibre (MN/m^2)	-	2690	1380	2070	1380
Unidirectional Composite Stress (MN/m^2) (1)	-	1830	870	1350	900
Ultimate Composite Hoop Stress (MN/m^2)	1850	1190	570	890	580
Hoop Strain at 75% ultimate Stress	0.007	0.0224	0.0042	0.006	0.0025
Effective Composite Hoop Modulus (GN/m^2)	207	40	101	110	172
Relative Density of Material (2)	8.0	2.08	1.55	1.58	1.72
Specific Ultimate Hoop Stress (MN/m^2)	231	580	380	560	360
Specific Hoop Modulus (GN/m^2)	26	20	65	70	100

Notes: (1) Glass/Resin - 66/34 Vol.%
Graphite/Resin - Actual 62.5/37.5 Vol.%
Potential 65/35 Vol.%

(2) Relative Density - S.994 - 2.5, Type II - 1.77, Type 1 - 2.0
Resin - 1.2

(3) Actual Type II - Morganite treated

3.2 Support Structures

Not all rocket applications of high modulus fibre, however, will normally be concerned with filament winding, although this naturally lends itself to the manufacture of the cases or to pressure vessels.

In addition to the motor cases, there are usually attachment fittings such as skirt rings and the actual support structures for the satellite or payload. Often, the design of these auxiliary items is a function of specific stiffness as much as actual strength, and the potentiality of high modulus carbon/resin laminates, probably based on a box or honeycomb construction, is obviously attractive. For the same reason fins and fin roots, shrouds and nose cones could fall into the same general category. A bi-directional high modulus carbon laminate of 65% carbon by volume has a specific composite modulus of over 3 times that of steel or aluminium.

4. GENERAL SURVEY AND CONCLUSIONS

In brief outline, this is the carbon fibre composite field in rocket motor systems. Brief outline is necessary in a paper of this length because in any one aspect of the foregoing sections, development is proceeding at a pace where progress can be measured in weeks rather than years - particularly in the latest area of high modulus fibre composites. Often, the choice of materials for particular projects is made difficult by this very speed of development as a decision may have to be made, not necessarily on today's state of the art, but what is likely in a few years time when the project is nearing production.

As will have been appreciated, not only are the carbon materials being improved and developed but also the resins, processing methods, and the fundamental designs associated with them. Most of the work to date has been based on the conventional phenolic and epoxide resin systems but already developments based on polyimides, polybenzimidazoles and polyphenylene resins are under way for high temperature, ablation and insulation. For structural applications more interest is being directed towards the cyclo aliphatic type of epoxide resins. The manufacturing methods have again been fairly conventional but already one of the properties of the carbon fibres is being exploited, namely, the electrical conductivity: work at Lockheed has indicated the practicability of using this as a means of generating the cure temperatures within the composite by the application of electrical voltage[4].

Perhaps one of the latest and most far reaching developments is in the process of composite carbonization, particularly for ablation and insulation applications. The composite is fabricated and cured in the normal way and then subjected to further heat treatment in an inert atmosphere in order to reduce the resin element of the composite of carbon. Repeated heat treatment and vacuum impregnation to fill the cavities can result in the formation of a very high quality structure of fibrous material bonded together with carbon or graphite. Initial firings of rocket motor throats in this material have shown most encouraging results.

4. GENERAL SURVEY AND CONCLUSIONS (Continued)

In order to decide on any material today many factors need to be considered. At the present time, if cost is to be the determining factor, carbon composite materials are usually well behind the leaders. Where, however, the ultimate criterion is efficiency on a weight basis, the carbon composites suddenly assume major importance. For such applications as satellites, satellite launchers, and re-entry vehicles the carbon composite is one of the first materials that should be considered.

In conclusion, a sketch, Fig. 7, is included that has been arrived at by fairly intelligent use of the well known crystal ball. A rocket motor case, end plate, and expansion cone were weight analysed on their present construction; the only carbon actually used is the throat, representing 2% of the weight. In a series of stages, more and more of the assembly was replaced by carbon composite materials until finally 72% of the total weight was carbon - most of the remainder, incidentally, being resin. At the same time the total weight has been reduced by 52%. To give some idea of the time scale involved, it is considered that Stage 1 and Stage 2 could be achieved now and the remainder within the next 10/15 years, all assuming that economy of manufacture is not the prime consideration.

Ultimately, the resin will probably be carbonized or graphitized as well and we shall finish with an all carbon structure - but it may then cease to qualify as a composite!

ACKNOWLEDGEMENT

The author thanks the Ministry of Technology and the Directors of Bristol Aerojet Limited for permission to publish this paper, also his colleagues at Bristol Aerojet and elsewhere for their assistance in the preparatory work involved.

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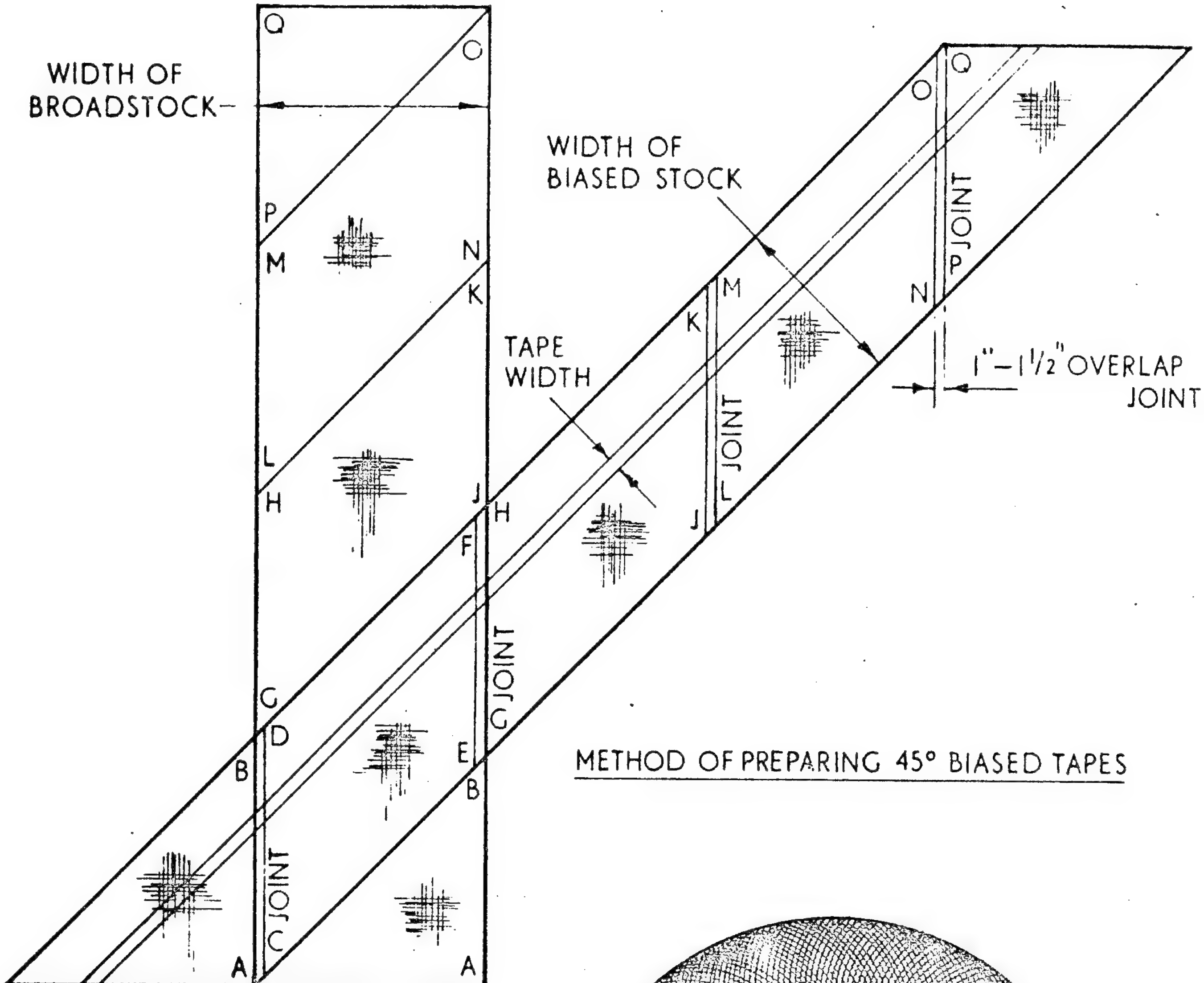
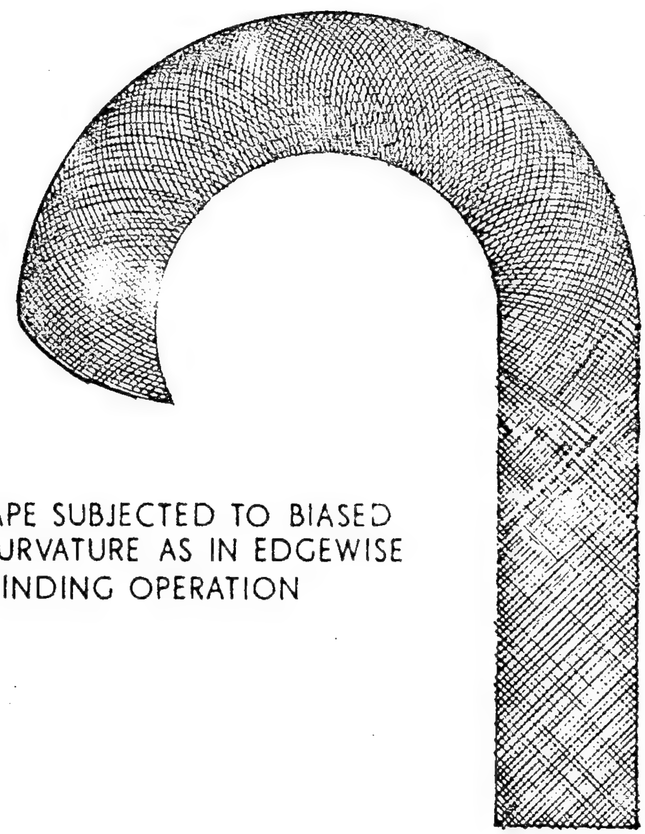


METHOD OF PREPARING 45° BIASED TAPES



TAPE SUBJECTED TO BIASED CURVATURE AS IN EDGEWISE WINDING OPERATION

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PRINCIPLE OF MANUFACTURE AND USE OF BIAS CUT TAPES

FIG. 1

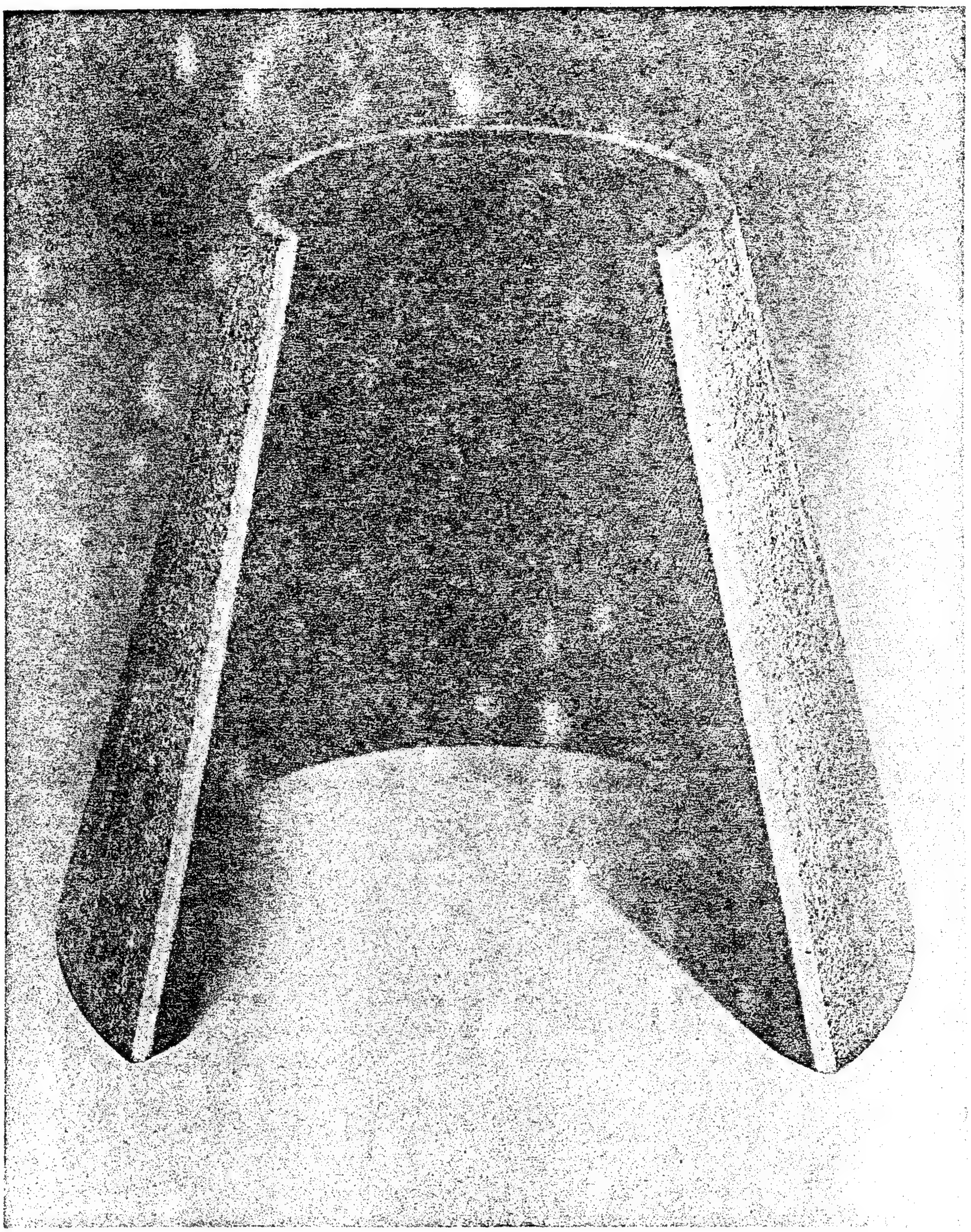


Fig. 2 Edgewise Wound Expansion Cone with Asbestos/Phenolic Overlay.

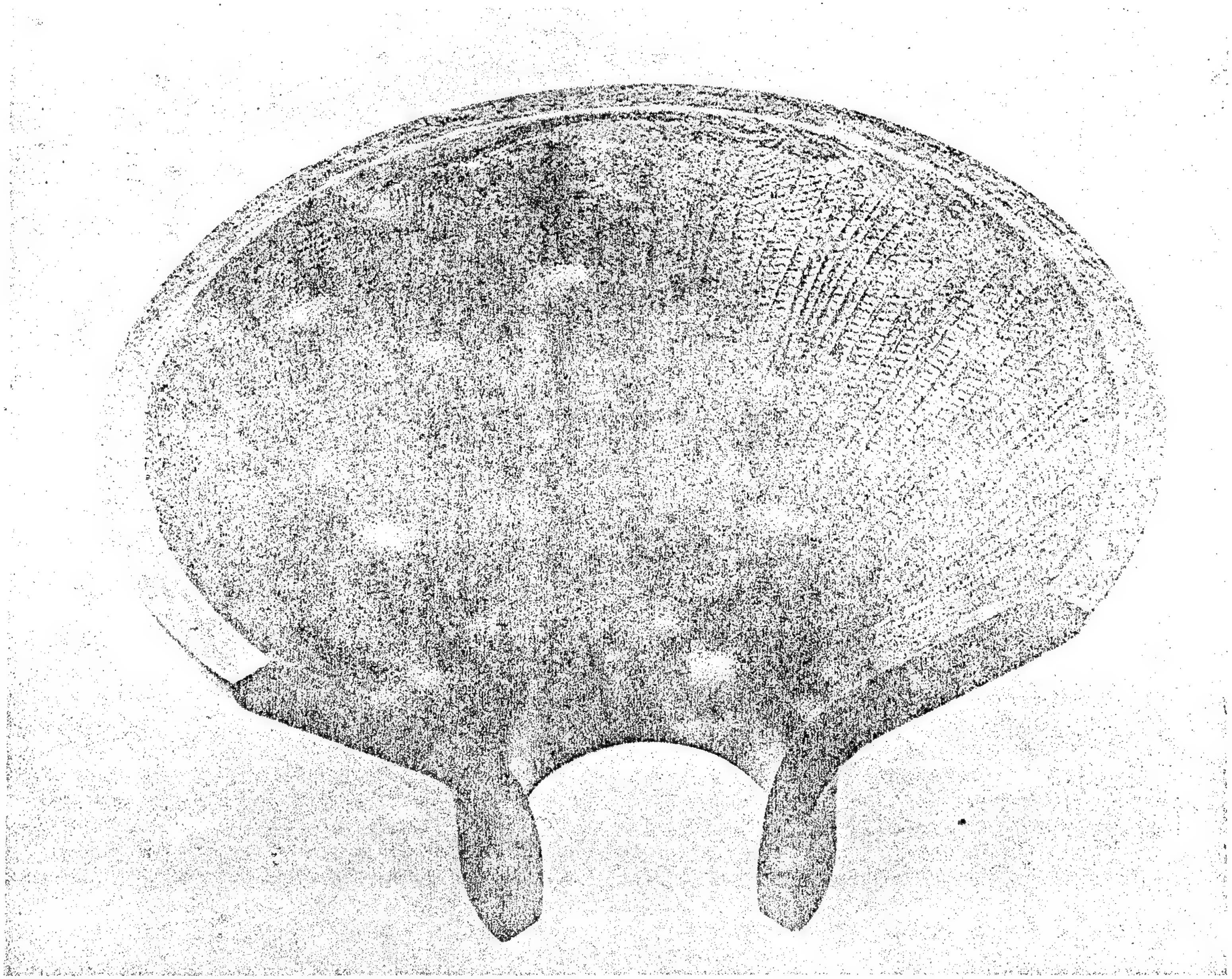


Fig. 3 Rocket Motor End Plate Liner in Graphite/Phenolic Rosette Lay-up.

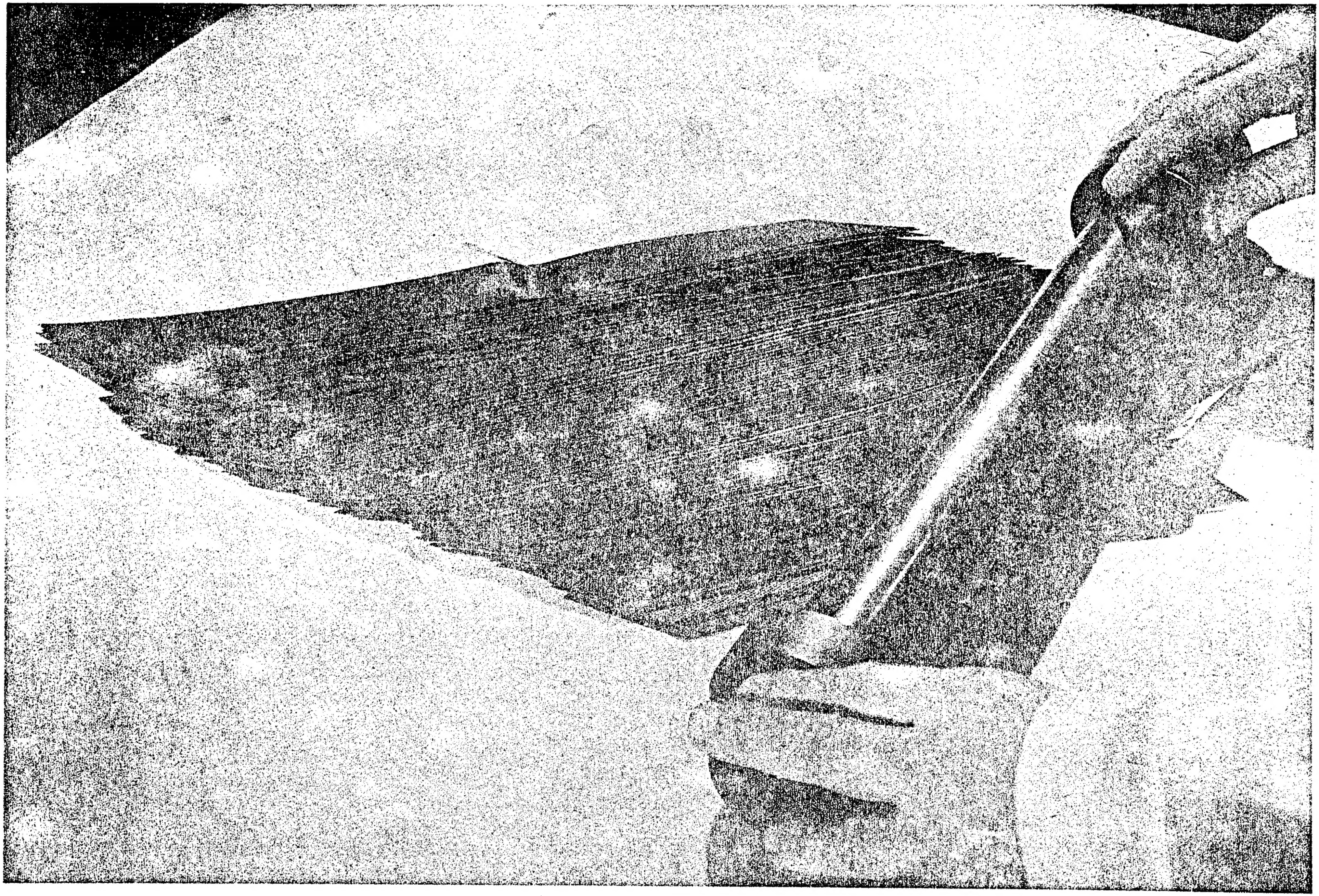


Fig. 4 Preparation of Rosette Lay-up Blast Pipe Liner

Fig. 5 View along Rosette Lay-up Blast Pipe Liner showing Spiralled Petals.

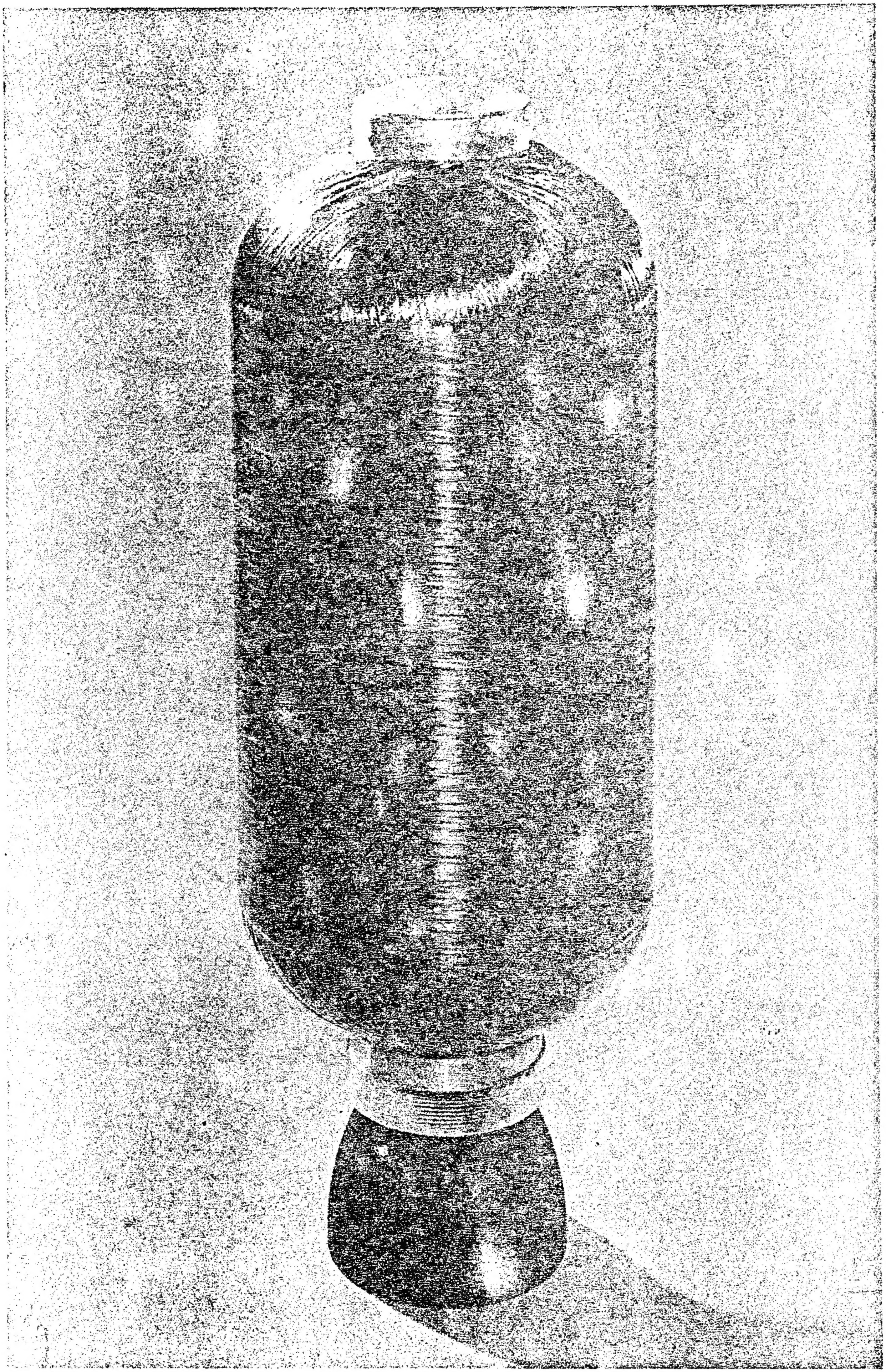
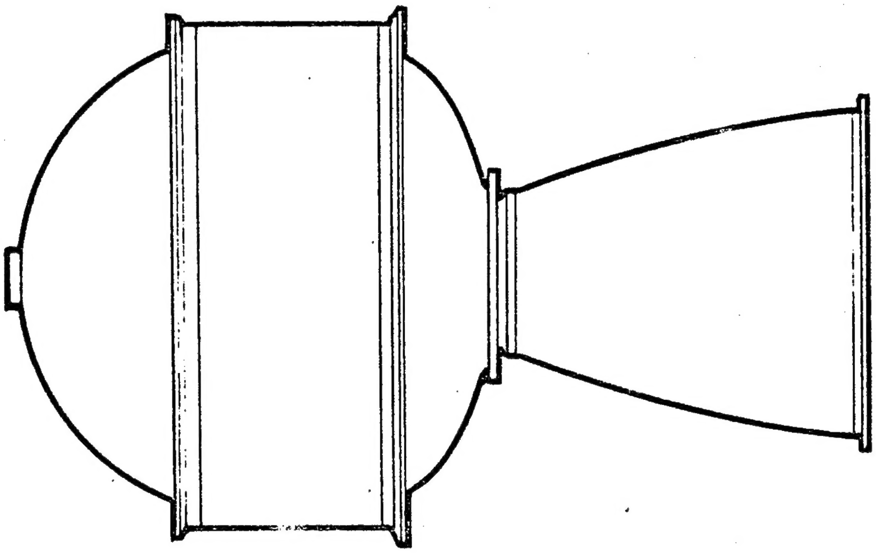
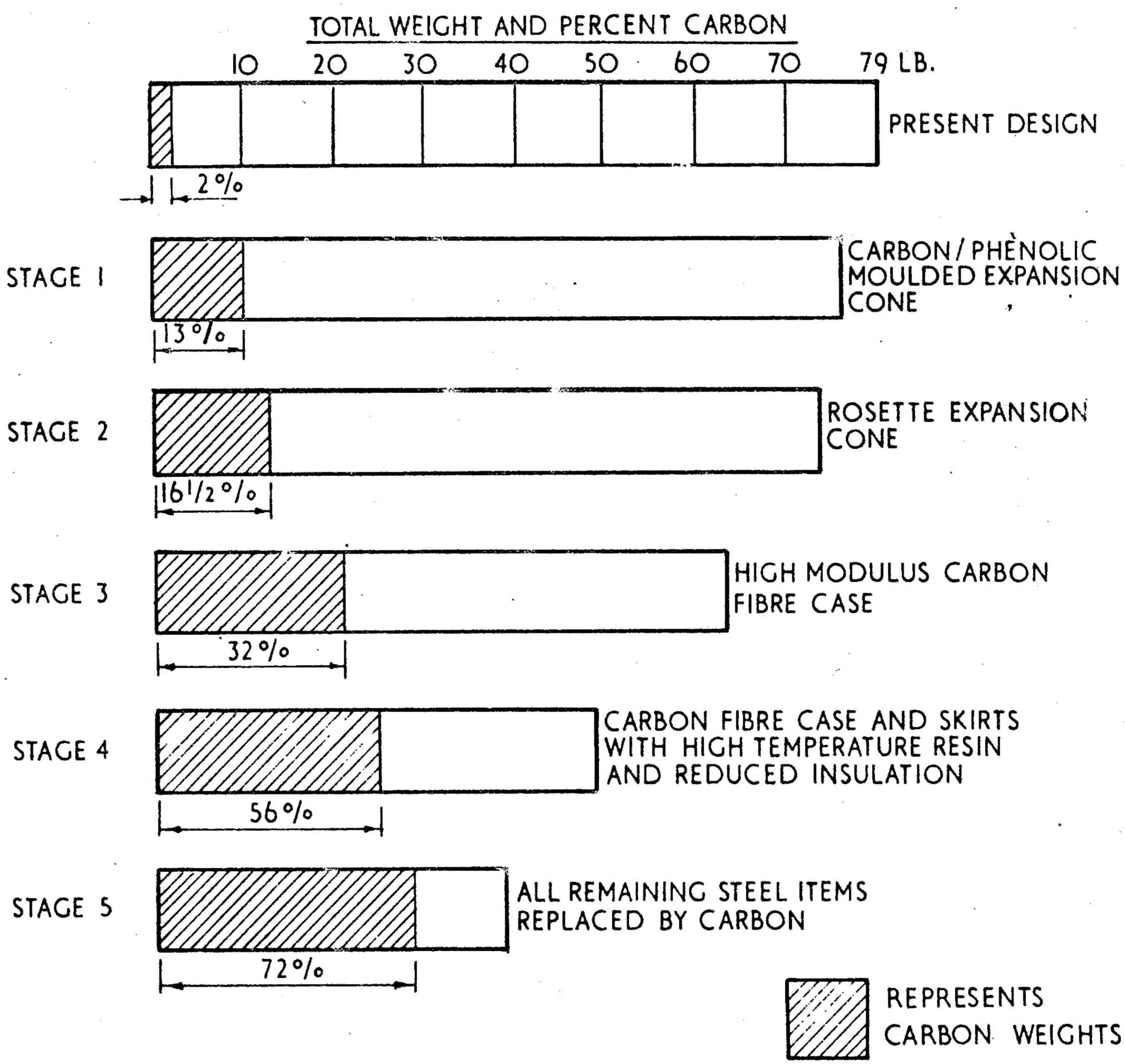


Fig. 6 6" dia. Carbon Fibre Motor Case with Rosette Lay-up Graphite/Phenolic Expansion Cone

FIG. 7

28 IN. DIA. ROCKET MOTOR AND EXPANSION CONE ASSEMBLY





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PROGRESSIVE USE OF CARBON

IN 28" DIA ROCKET MOTOR & EXPANSION CONE